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Cost analysis of air capture driven by wind energy under different scenarios

Yinghui GENG[1], Canbing LI[1], Yijia CAO[1], Hao CHEN[2], Yonghong KUANG[1], Xuedong REN[1], Xinwei BAI[1]

Abstract Reducing the concentration of carbon dioxide (CO_2) in the air can effectively alleviate climate change. Air capture, which captures CO_2 directly from the air in an industrial process, is an alternative option to address climate change. The results of recent studies on the energy demand in CO_2 capture process and the costs of CO_2 transport and CO_2 storage in air capture are analyzed in this paper. Considering renewable energy will not produce additional CO_2 in the process of utilization, the electric energy in CO_2 capture process of air capture driven by wind energy is different from that of carbon capture and storage. Taking externalities of renewable energy into account, the trading price of CO_2 emission is taken to assess the cost of electric energy in CO_2 capture of air capture driven by wind energy. Finally, the total cost and the total cost savings of air capture driven by wind energy under different scenarios are analyzed.

Keywords CO_2 capture and storage, Renewable energy, Wind power, Air capture, CO_2 emission

1 Introduction

Burning large amounts of fossil fuels releases CO_2 to air, which is the main cause of greenhouse effect. Some literatures pointed out that the global temperature will probably increase 2 °C compared with the pre-industrial level due to greenhouse gas emissions by 2050 [1–3]. And the possibility that the global temperature would increase 2 °C will be as high as 75% if CO_2 emissions are not less than 50 Gt by 2020 [1]. Controlling greenhouse gas emissions becomes one of the most challenging environmental problems that the world is facing [4].

Carbon capture and storage (CCS), as a potential method to address climate change, is gaining widespread interest all over the world. CCS can handle 85%～95% of CO_2 in the exhaust gases produced by coal-fired power plants and other industrial enterprises [5]. The International Energy Agency (IEA) predicted that if CCS could capture, transport, and store more than 8 Gt of CO_2 every year, 19% of global CO_2 emissions would be reduced by 2050 [5, 6].

With the rapidly rising concentration of CO_2 in the air, which has reached approximately 400 ppm, air capture has also attracted wide attention. Air capture, with its installation site unlimited to large stationary sources, can capture

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✉ Canbing LI
licanbing@gmail.com; licanbing@qq.com

Yinghui GENG
861450466@qq.com

Yijia CAO
yjcao@hnu.edu.cn

Hao CHEN
haochen@aimlab.org

Yonghong KUANG
117394099@qq.com

Xuedong REN
980560600@qq.com

Xinwei BAI
784662753@qq.com

1 College of Electrical and Information Engineering, Hunan University, Changsha 410082, China

2 College of Computer Science and Electronic Engineering, Hunan University, Changsha 410082, China

CO_2 from the mobile sources [7–9]. Even relatively unsafe CO_2 storage, for example, the storage capacity is 1% reduction of the CO_2 in the air per 1000 years, can help to mitigate medium-term climate change at least [5, 10, 11]. Air capture driven by fossil fuels, however, consumes plenty of energy and produces additional CO_2.

Current economic analysis on CO_2 capture system has been conducted by many researchers, but they usually study the system driven by electricity or conventional energy [12]. Air capture driven by renewable energy has the potential to avoid dangerous climate change. Renewable energy, such as wind and solar energy, has the characteristics of cleanness and huge development potential, without producing additional CO_2 in the process of utilization. It is possible for carbon capture device to function normally when it is only powered by intermittent sources. Researchers have demonstrated that concentrated solar energy is a viable energy source to provide high temperature process heat. CO_2 capture from air powered by concentrated solar was proposed to supply the thermal energy [13, 14]. Co-location of air capture system powered by wind energy is proposed and it can capture approximately 75 Mt of CO_2 every year in Kerguelen plateau, a remote ocean site with steady wind resources [15]. The brief technical details of air capture driven by renewable energy are as follows:

1) Air capture devices driven by renewable energy can be regarded as a simple load, and it can work like microgrid dispatching load.
2) Air capture devices consume a large part of energy in the form of heat and heat energy can keep constant temperature within minutes. So carbon capture devices, to a certain extent, can function normally when it is only powered by intermittent sources.
3) Energy analysis on CO_2 capture from air systems is performed [16, 17]. CO_2 capture from air system is composed of contactor, causticizer, slaker, calciner, kiln, and compressor. The energy requirements, energy types, acceptable active power fluctuation rate for each device are different, and it could not work normally within the acceptable lower and upper limits. Air capture driven by renewable energy has attracted attention, but its feasibility is only studied from technical view, not from economic view.

Our primary goal in this paper is to present an approach to reduce the cost of air capture devices in a feasible manner. In this paper, the energy demand in CO_2 capture process and the costs of CO_2 transport and CO_2 storage in air capture driven by wind energy are analyzed. Then, four scenarios of air capture driven by wind energy are proposed, and the cost and the cost savings of each process are calculated under each scenario.

2 Cost analysis of each stage in air capture driven by wind energy

The process of air capture driven by wind energy includes CO_2 capture, CO_2 transportation and CO_2 storage. And the function of wind energy driven air capture system is shown in Fig. 1, which reflects each cost component involved in the paper.

2.1 CO_2 capture

The main advantage of air capture driven by wind power is that it can capture CO_2 without producing additional CO_2. Comparing the equal power generation of fossil fuel with wind energy, wind power releases almost zero CO_2 emission to the environment. Externalities of renewable energy should be taken into consideration when evaluating the cost of electric energy in CO_2 capture process.

2.1.1 Cost proportion in onshore and offshore wind farms

The cost of wind power is mainly determined by investment cost, operation and maintenance cost, turbine lifetime, and discount rate. The cost percentage of each part in onshore and offshore wind power projects is shown in Table 1 [18]. If the grid-connection cost can be saved, air capture driven by wind energy could reduce the cost of wind power.

These data statistics are from onshore and offshore wind power projects in developed countries in 2011. Air capture devices driven by wind energy have the following advantages: ① Carbon capture devices are kind of flexible load, which can to some extent utilize intermittent energy sources such as wind energy and solar energy; ② Wind power will bring power grid operation management and

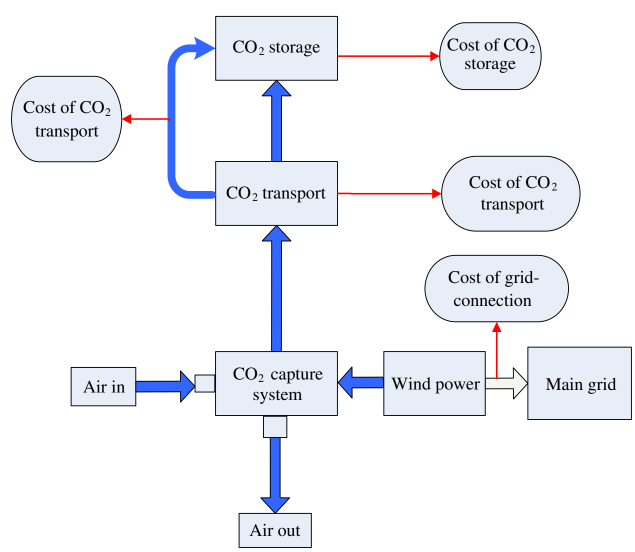

Fig. 1 Function of wind energy driven air capture system

Table 1 Cost proportion of each part in onshore and offshore wind farms

Parameters	Onshore	Offshore
Capital investment costs ($/kW)	1700～2450	3300～5000
Wind turbine cost share (%)	65～84	30～50
Grid connection cost share (%)	9～14	15～30
Construction cost share (%)	4～16	15～25
Other capital cost share (%)	4～10	8～30

scheduling an unprecedented uncertainty when connected to the grid due to its intermittency and volatility [19]. Wind electricity can be fully used to capture CO_2 if air capture devices are driven by wind power, so it can avoid curtailed electric energy. Curtailed electric energy means large amounts of electricity from renewable sources are wasted due to the real-time balance between generation and load.

2.1.2 Direct cost of wind power generation-onshore

The direct cost of wind power generation is calculated based on life cycle cost analysis, which equally divides the whole expense of wind power generation over the whole life cycle. In this paper, the direct cost of wind energy is roughly estimated without considering the loan and interest. It is mainly determined by the following parameters [18, 20]:

1) Capital cost. It includes wind turbines cost, foundations cost, road construction cost, and grid-connection cost, accounting for 80% of the overall cost of wind power project.
2) O&M cost. Although the O&M cost is not clearly defined, it consists of material cost, equipment operation and maintenance cost, wages, and rent in most cases.
3) Life cycle of wind power project.

As wind power does not need fuel, which is the basic difference between fossil fuel generation and wind power, there is no need to consider the fuel cost in this paper. In the meantime, air capture devices driven by wind energy can save the cost of grid-connection, so the total investment cost can be calculated by

$$C_Z = C_C + C_{O\&M} - C_G \tag{1}$$

where C_Z is the total investment cost; C_C is the capital cost of wind farms; $C_{O\&M}$ is the O&M cost; C_G is the cost of grid-connection.

The unit cost of wind farm investment is equal to the wind power investment cost per kWh, which can be expressed as follows:

$$C_D = \frac{C_C + C_{O\&M} - C_G}{Q} \tag{2}$$

where C_D is the unit cost of wind farm investment; Q is the cumulative electrical production and it can be formulated as follows:

$$Q = NQ_i \tag{3}$$

where N is the lifetime of wind turbine; Q_i is the electrical generating capacity per year, which can be expressed as follows:

$$Q_i = TP_n \tag{4}$$

where P_n is the wind turbine capacity; T is the full load hours for onshore installations.

The direct cost of wind power generation is estimated based on the following data [18, 20]. At the moment the average size of wind turbine ranges from 2 MW and 3 MW, with 2 MW selected in this paper; the lifetime of wind turbine is 20 years; the capital cost of wind farm is $760～970/kW; the O&M cost is approximately $10/MW h in the 2000 s; the cost of grid-connection is about $115.24/kW; the average number of full load hours for onshore wind installations is between 1700 and 3000 hours/year, with 2000 hours/year selected in this paper. Thus, when wind farms are not connected to the grid, the direct cost of wind power generation is in the range of 2.61～3.14 cents/kWh using (1)～(4). If when wind farms are connected to the grid, the range of direct cost of wind power generation is 3.10～6 cents/kWh using the data from [20].

2.1.3 External cost of wind power generation

The externalities of wind energy should be taken into account to evaluate the external cost of wind energy. External cost is the cost of the impact coming from the environment because of the pollutants emitted from the specified technology [21]. Coal-fired power plants release CO_2 emissions into the air. However, Wind power generation almost release no CO_2 emissions. In other words, wind power generation for one kWh can reduce CO_2 emissions of equal amount kWh from coal-fired power plants. Thus, the external cost of wind power generation can be calculated by:

$$C_W = P_W Q_W \tag{5}$$

where C_W is the external cost of wind power generation; P_W is the charge standard for CO_2 emissions per kg; Q_W is the CO_2 emission reduction by wind power generation per kWh.

The value of CO_2 external cost is $0.018/kg, and coal-fired power plants release CO_2 0.86～1.29 kg/kWh [21, 22], so wind power generation for 1 kWh can reduce equal amount of CO_2 emissions into the air. Thus, the external cost of wind power generation ranges from 1.55 to 2.32 cents/kWh based on (5).

2.1.4 Electricity consumption in CO_2 capture stage

Carbon capture devices consume large amounts of electricity CO_2 capture process. For example, the electricity consumption of CCS follows a downward trend, with 306 kWh/t of CO_2 in 2005 and 196 kW h/t CO_2 after 2014, according to the IEA Greenhouse Gas R&D Programme (IEA GHG) [23]. However, if CO_2 is captured directly from air, more energy is needed. Air capture can be driven by natural gas, solar, wind, and other energy. And the energy requirements of air capture driven by different energy range from 110 kJ/mole CO_2 when 2nd-Law Efficiency is 50% to 2485 thermal kJ/mol CO_2 when 2nd-Law Efficiency is 2.4%, driven by solar energy [24]. The energy requirement of air capture driven by wind energy is 442 kJ/mol CO_2, which equals to 2790 kWh/t of CO_2 [25].

2.1.5 Cost of electric energy in CO_2 capture process

The cost of electric energy needed to capture per ton CO_2 can be calculated as follows:

$$C_S = C_e e \tag{6}$$

where C_S is the cost of electric energy, which air capture needs to capture per ton of CO_2; C_e is the social cost of wind energy per kWh; e is the electric energy which air capture needs to capture per ton of CO_2. Social cost of carbon, as defined by [26], is the monetary value of world-wide damage done by emitting one more ton of carbon. It is the difference between the direct cost and the external cost.

The social cost of wind energy is the difference between the direct cost and the external cost of wind power generation. Thus, the value of social cost of wind energy has the following two scopes: when wind farms are not connected to the grid, the cost is 0.84$\sim$1.06 cents/kWh; and 1.55$\sim$3.68 cents/kWh when wind farms are connected to the grid. In CO_2 capture process, 2790 kWh of electric energy is needed to capture per ton of CO_2. Thereby, the cost of electric energy needed to capture per ton of CO_2 under the two situations are obtained using (6). When wind farms are not connected to grid, the cost of electric energy is \$23.44$\sim$29.57/t of CO_2 and \$43.25$\sim$102.7/t of CO_2 when wind farms are connected to grid. The corresponding increase of the cost is \$43.25/t to \$64.73/t of CO_2, respectively, without considering the externalities wind energy.

2.2 CO_2 transport

Large amounts of CO_2 captured by air capture devices need to be transported to the storage site, and pipeline transport is the most economic transportation method for onshore air capture [26]. The cost of pipeline transport is mainly determined by the physical and social terrain that the pipelines go through, the characteristic of pipeline, and the number of booster stations. Taking the environment and safety factor into consideration, pipe is usually buried underground for a relatively stable temperature [26]. For a 500 MW gas fired combined cycle power station, it costs 6 dollars to transport per ton of CO_2 [27].

2.3 CO_2 storage

There are some geologic CO_2 storage methods: depleted gas/oil reservoir, saline aquifer storage, ocean storage via pipeline, ocean storage via tanker [28]. The cost of each CO_2 storage method is shown in Table 2.

The cost range of CO_2 storage is \$2$\sim$15/t CO_2 excluding the most expensive ocean tanker method [28].

3 Cost analysis of air capture driven by wind energy under different scenarios

3.1 Scenario analysis of air capture driven by wind energy

CCS is usually installed around large stationary sources such as power plants and other enterprises. The installation site of air capture is less restrictive. Therefore, air capture can be installed in CO_2 storage sites, which will save transportation cost. It will save the cost of grid-connection if wind farms are not connected to the grid. Thus, in this section, four scenarios are proposed to reduce the costs of air capture driven by wind energy in Table 3.

Table 2 Cost of CO_2 storage with different methods

Methods	Base cost (\$/t CO_2)	High cost (\$/t CO_2)	Low cost (\$/t CO_2)
Depleted gas reservoir	4.87	19.43	1.20
Depleted oil reservoir	3.82	11.16	1.21
Deep saline aquifer	2.93	11.71	1.14
Ocean storage via pipeline	5.53	14.23	2.90
Ocean storage via tanker	17.64	22.79	15.76

Table 3 Definition of four scenarios

Scenario	Cost of grid-connection	Cost of CO_2 transport
I	√	√
II	√	△
III	△	√
IV	Generating cost is 0	△

"△" represents the grid-connection cost or the CO_2 storage cost cannot be saved; "√" represents the grid-connection cost or the CO_2 transport cost can be saved

Scenario I: When air capture devices driven by wind energy are installed in the sites suitable for CO_2 storage, and wind farms are not connected to grid, the costs of grid-connection and CO_2 transport can be saved.

Scenario II: When air capture devices driven by wind energy are installed in the sites unsuitable for CO_2 storage, and wind farms are not connected to grid, only the cost of CO_2 grid-connection can be saved.

Scenario III: When air capture devices driven by wind energy are installed in the sites suitable for CO_2 storage, and wind farms are connected to grid, only the cost of CO_2 transport can be saved.

Scenario IV: When wind farms are connected to grid, the cost of electric energy is \$43.25 ~ 102.7/t CO_2. Air capture devices driven by wind energy can utilize curtailed electric energy. Thus, in CO_2 capture process, the cost of electric energy is 0 and the cost of \$43.25 ~ 102.7/t CO_2 can be saved. When air capture devices driven by wind energy are installed in the sites unsuitable for CO_2 storage, the costs of CO_2 transport and CO_2 storage are still needed.

3.2 Cost prediction of air capture

At present, air capture is still in its initial stage.

Although it is technologically feasible, the economic feasibility in large-scale still needs to be further explored for air capture to play an important role in CO_2 capture in the future [7, 29]. The predictable cost of air capture varies tremendous and is in the range of \$30 ~ 1000/t of CO_2 [7]. The American Physical Society (APS) estimates that the cost of air capture is nearly \$600/t of CO_2 [31] and there is a high possibility that the cost will be much more than \$100/t of CO_2 [30]. In the coming decades, air capture could plausibly achieve \$200/t of CO_2 to \$500/t of CO_2 [8]. If the cost of air capture is less than \$50/t of CO_2, it will be more competitive among climate mitigation technologies.

3.3 Cost of air capture driven by wind energy under four different scenarios

In this paper, the total cost of air capture is \$600/t of CO_2 according to the data in [29, 30]. The total cost and the cost savings of air capture driven wind energy are shown in Table 4 and Table 5 based on whether considering the

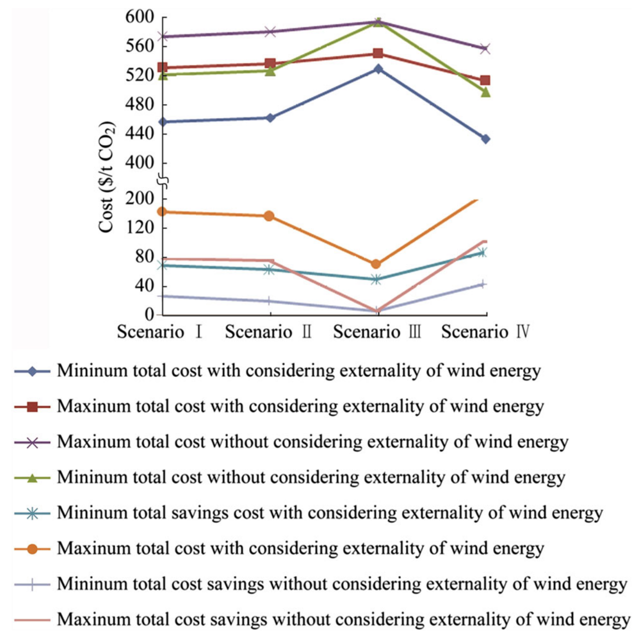

Fig. 2 Results of four scenarios

Table 4 Total cost and cost savings of air capture driven wind energy considering externality of wind energy (\$/t CO_2)

Scenario	External cost of wind power generation	Cost of grid-connection	Cost of CO_2 transport	Cost of CO_2 storage	Total cost savings	Total cost
I	43.25 ~ 64.73	19.81 ~ 73.13	6	×	69.06 ~ 143.86	456.14 ~ 530.94
II	43.25 ~ 64.73	19.81 ~ 3.13	×	×	63.06 ~ 137.86	462.14 ~ 536.94
III	43.25 ~ 64.73	×	6	×	49.25 ~ 70.73	529.27 ~ 550.75
IV	43.25 ~ 64.73	43.25 ~ 102.7	×	×	86.5 ~ 167.43	432.57 ~ 513.5

Table 5 Total cost and cost savings of air capture driven wind energy without considering externality of wind energy (\$/t CO_2)

Scenario	External cost of wind power generation	Cost of grid-connection	Cost of CO_2 transport	Cost of CO_2 storage	Total cost savings	Total cost
I	×	19.81 ~ 73.13	6	×	25.81 ~ 79.13	520.87 ~ 574.19
II	×	19.81 ~ 73.13	×	×	19.81 ~ 73.13	526.87 ~ 580.19
III	×	×	6	×	6	594
IV	×	43.25 ~ 102.7	×	×	43.25 ~ 102.7	497.3 ~ 556.75

externalities of wind or not and the above analysis under four scenarios.

Each value in the table represents the cost saving or total cost under different scenarios, and "×" represents the cost that cannot be saved.

Finally, the results of four scenarios are shown in Fig. 2 to visually compare the differences in the total cost and the cost savings of each scenario.

4 Conclusion

Air capture, as a mitigation technology, has the potential to stabilize and reduce greenhouse gas emissions. Wind energy, without producing additional CO_2 in the process of utilization, can drive air capture to capture CO_2 to reduce the concentration of CO_2 in the air. Taking externalities of renewable energy into account, the total cost and the total cost savings of air capture driven by wind energy are calculated under four scenarios in this paper. With the previous different scenarios, the following conclusions are:

1) Considering externality of wind energy, Scenario IV is the most cost-effective. It could save \$86.5 ~ 167.43/t CO_2, which accounts for 20% ~ 32.1% of the total cost.
2) Without considering externality of wind energy, Scenario III saves the least cost, which saves \$6/t CO_2.

Scenario IV considering externality of wind energy costs the least, so it should be developed and applied preferentially.

At present, the cost of air capture is still very high. Its cost may decline with a lower price of renewable energy sources, the optimization design and scheduling of CO_2 capture devices.

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Yinghui GENG received the B. Eng degree from Northwest University for Nationalities in 2013. Now she is pursuing her master degree in Hunan University. Her research interest is power system dispatching.

Canbing LI received B. Eng and PhD degrees in Electrical Engineering from Tsinghua University in 2001 and 2006 respectively. Currently, he is a professor of Hunan University. His research interests include smart grid and energy sustainability.

Yijia CAO received PhD degree from Huazhong University of Science and Technology in 1994. He became a special-term professor of the ''Cheung Kong Scholars Program'' in Zhejiang University in 2001. Since March 2008, he has been serving as Vice President of Hunan University. His research interests include power system cascading failure, power system information technology, computational intelligence and its applications to smart grid optimal operation.

Hao CHEN received the BS degree from Sichuan University in 1998, and the PhD degree from Huazhong University of Science and Technology in 2005. He is now an associate Professor of Hunan University, China. His research interests include parallel and distributed computing, operating systems, cloud computing and systems security.

Yonghong KUANG received the BS degree and Master degree in 2003 and 2007 respectively. She is a lecturer of Hunan Institute of Engineering. She is also working toward the PhD degree in Hunan University. Her research interest is optimal scheduling of micro grid.

Xuedong REN received the B. Eng degree from Shandong Agricultural University in 2014. Now he is pursuing his master degree in Hunan University. His research interest is power system dispatching.

Xinwei BAI received the B. Eng degree from Hunan University in 2014. Now, he is pursuing master degree in Hunan University. His research interest includes power system dispatching.